Propulsion Trades for Space Science Missions

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Abstract

This study evaluated the relative benefits of proposed deep space propulsion technology improvements in three areas: advanced chemical, solar electric, and solar sail. Within each area, specific states, representing current technology (present-1999), mid-term (2000-2004), and far term (2005+), were selected for evaluation. The figures of merit used were net spacecraft mass delivered, size of the launch vehicle needed, trip time, cost, and risk. Based on the results, an investment strategy was recommended to NASA headquarters, along with possible scenarios for its implementation.

1. Introduction

In response to a NASA headquarters request, the Jet Propulsion Laboratory (JPL) conducted a propulsion trades study to evaluate the relative benefits of proposed deep space propulsion technology improvements and recommend an investment strategy. For convenience, three technology readiness time periods were delineated for review: current technology (present - 1999), mid-term (2000 - 2004), and far term (2005+). After preliminary assessment, the study identified three technology areas of interest: advanced chemical, solar electric, and solar sail. Within these areas, the relevant development steps for each time period were defined with the assistance of the technology community.

For the evaluations, the figures of merit used were net spacecraft mass delivered, size of the launch vehicle needed, trip time, cost, and risk. As defined, net spacecraft mass did not include the propulsion system hardware or accompanying structure. Launch vehicles larger than an Atlas 2AS/Star 48B were not considered. Costs were estimated for incremental technology development, flight system (first unit and recurring), and operations increases. With these figures of merit, the technology state capabilities were compared between the different areas and for mid-term vs. current and far term vs. mid term for a variety of deep space missions.

The missions chosen for review represent a cross section of type (lander/orbiter/flyby) and target (planets/moons/sun), with emphasis on those identified in the Space Science Strategic Plan (Ref. 1). For a few of the missions, such as the Solar Polar Imager, advanced technology developments are enabling. However, for most of the missions reviewed, there is a trade off between the performance enhancements and the cost.

In this report the selected technology states, the methods of calculation, and the cost estimates are described. Results for each of the missions are presented, followed by a synthesis of the results leadind to conclusions about the main benefits. Finally, the recommended investment strategy is given.

2. Technology States

The propulsion technologies considered in this study are described below. Figure 1 shows the current development schedule for these technologies based on optimistic funding profiles.

2.1 Chemical Propulsion

The baseline chemical system used in this study is an NTO/hydrazine engine with an Isp of 325 s, which is slightly higher than what is currently being flown, but will be achieved in the current technology timeframe. A LOX/hydrazine engine with an Isp of 350 s is the mid-term chemical technology. This system is an intermediate step toward development of the far term fluorine/hydrazine engine (Isp = 393 s). Near term ascent system advances, which are enabling for the Mars Sample Return (MSR) '05 mission as well as any future large-body sample return missions, will feature low temperature (~ 40 °C) propellants, a lightweight 500 lbf thruster, warm gas pressurization, and lightweight tanks and components.

2.2 Solar Electric Propulsion

The NSTAR SEP hardware, scheduled to launch on the New Millennium Deep Space 1 mission on 1 July 1998, is used as the baseline current technology. A slight modification is that multiple thrusters are allowed. The total xenon throughput of this engine is 83 kg. Two mid-term SEP advances were considered: NSTAR2 and NSTAR3. NSTAR2 is a 30 cm ion engine NSTAR derivative being planned for use on the Champollion-lander Deep Space 4 mission. It has a xenon throughput of greater than 120 kg and a four-fold reduction in gimbal mass relative to NSTAR. NSTAR3 is a quarter-scale (14 cm) derivative system selected on the expectation that it would show a benefit for deep space missions performed using the smaller launch vehicles. This system assumes a 50 kg xenon throughput capability and a gimbal mass that is 50% of the engine mass. The far term SEP advance studied was a direct-drive TAL system which assumed two different engine sizes: a 2.3 kW engine with a total xenon throughput of 100 kg and a 1.1kW engine with a total xenon throughput of 50 kg (used for the smaller launch vehicles). Gimbal mass was assumed to be 30% of the engine mass.. Additionally, the direct-drive power processing unit (PPU) for this system has a factor of five lower specific mass relative to the NSTAR system.

2.3 Solar Sail Propulsion

It is not anticipated that solar sail development will begin in earnest until the mid-term timeframe. However, a sail areal density of 15 g/m^2, with an 8 μm film thickness, could be built and is used to represent current technology. Note that the areal density, sometimes referred to as the sail loading, is the ratio of the sail assembly mass, which includes the mass of the sail and supporting structure, to the sail area. Mid-term sails are assumed to have an areal density of 10 g/m^2, which requires about a 4 μm film thickness. Far term sails are assumed to have an areal density of 5 g/m^2 or less, which requires about a 1 - 2 μm film thickness.

2.4 Data Sources and Calculation Methods

2.4.1 Chemical Propulsion. To approximate the performance of the advanced chemical systems, existing mission design studies were used to identify the parameters of flight time, trajectory type, launch vehicle C_3, and post launch ΔV for each mission of interest. Using the given C_3, injected masses were obtained for the five launch vehicles under consideration: an Atlas 2AS/Star 48, a Delta 2 7925, a Delta 2 7326, a Taurus/Star 37, and a Pegasus XL/Star 27. A 10% contingency was deducted for each injected mass.

For comparison purposes, the launch vehicles were assumed to be idealized rockets so that the final mass delivered to the target could be obtained from the rocket equation. However, this final mass includes the propulsion system. An approximate propulsion system mass can be calculated by assuming that the bulk of the propulsion system structural mass is 16% of the propellant mass and that another 20 or 40 kg will cover all the other necessary structures, including cabling. An additional 4% of the propellant, the cabling, and the structural mass was added for contingency. The delineation between large and small spacecraft was somewhat arbitrarily chosen to be a final mass of 350 kg. Then, the net spacecraft delivered mass is assumed to be the difference between the final mass and the propulsion system mass.

These calculations were done for all three chemical states identified, i.e. for Isp's of 325 s, 350 s, and 393 s. In addition, if the post launch ΔV was less than 300 m/s, the problem was also worked for a simple hydrazine engine (Isp = 220 s).

2.4.2 Solar Electric Propulsion. The best low-thrust SEP trajectory options for each destination in the mission set were determined by Carl Sauer (using SEPTOP) at JPL. These trajectories were calculated for either the Delta 2 7925 or Delta 2 7326 launch vehicles and NSTAR thruster performance. These results were then scaled for the advanced SEP technologies. The trajectory calculations included the following assumptions and deratings:

- The launch vehicle capability is derated 8 to 10%.
- End-of-life NSTAR thruster performance is assumed for the entire mission.
- The BOL solar array power (referenced to 1 AU) is assumed to be 1.3 times the end-of-life power required (referenced to 1 AU) due to radiation damage.
- Many of the trajectories derate the SEP system by an additional 10% to account for navigational coast periods.
- Pegasus XL-launched missions have no redundancy in the SEP systems. All other missions carry one extra engine.
- The system performance is scaled for different launch vehicles under the assumption that each launch vehicle's injected mass capability curve versus C3 has the same shape. This scaling is assumed to be independent of C3 for each launch vehicle (The ratios are constant.). This is a reasonable assumption if the Isp of the upper stages for each launch vehicle are comparable.

In order to use the same trajectories for the different propulsion types, it was assumed that each thruster performs such that the vehicle accelerations are the same as with the NSTAR system. Thus, the total delivered masses are fixed, and the benefits from the use of advanced SEP technology manifest themselves in lower dry masses, resulting in larger net spacecraft masses delivered. While the assumption is not a true representation of the thruster performance, more detailed calculations comparing direct-drive TAL systems with NSTAR suggest that it is not so incorrect as to invalidate the conclusions.

In all of the SEP states, the use of an advanced solar array (17% efficiency) was assumed. The mid-term and far term advances also assumed that an improved xenon feed system would be available and that the throttle range would be the same as an NSTAR engine. Additionally, the mid-term capabilities scaled the PPU as the square root of the power ratio relative to the NSTAR PPU. To calculate the SEP system masses for each mission, these additional assumptions were made:

- Each SEP system includes: engines, a gimbal for each engine, PPUs (approximately half as many PPUs as engines), a DCIU, PPU thermal control, xenon tankage, xenon feed system structure, cabling, non-PPU thermal control, and the solar array (including the articulation mechanism).
- The current best estimates from the NSTAR project are used for the NSTAR components, along with the NSTAR-recommended contingencies for each component. Non-NSTAR components are generally assumed to have a mass contingency of 30%.
- Propellant tankage is always assumed to be 10% of the stored propellant mass.
- The SEP system structure mass is assumed to be 7.5% of the SEP dry mass and is included with the SEP system.
- The NSTAR Digital Control and Interface Unit (DCIU) mass is used for each system.
- All PPUs except the NSTAR baseline are assumed to be internally redundant. The NSTAR baseline PPU is partially internally redundant.

2.4.3 Solar Sail. The best solar sail trajectory options for each destination in the mission set were also determined by Carl Sauer at JPL. The trajectory calculations assumed a C_3 value of zero for each mission, from which the maximum spacecraft masses were obtained by identifying the launch capability for the chosen C_3 and then subtracting approximately 10% for a contingency. These maximum values were used in the calculations as the total spacecraft mass. Additionally, each sail is assumed to be square in shape and have a 0.9 efficiency.

Each chosen trajectory gives a trip time and a characteristic acceleration (a_c), where a_c is the maximum acceleration at one AU. Using this a_c, the total spacecraft mass, the efficiency, and the solar constant, the area of the sail can be obtained. Once the area is calculated, the mass of the sail assembly is given by multiplying the sail area by the areal density, adjusting for units.

3. Cost Estimates

Cost estimates for the different states were provided by experts in the different areas. The estimates were separated into four budget areas: 1) cost to develop the system from current technology, 2) cost to build the first flight unit, 3) cost to build any additional flight units, and 4) cost above the current amount required to fund operations for the new technologies. A summary of these costs is given in Table 1. In the incremental technology development column, each of the SEP states is independent of the others. For example, NSTAR3 could be developed from current technology for $24M without having to develop NSTAR2 first. The Mars Sample Return (MSR) '05 ascent systems are similarly decoupled. However, the LOX/Hydrazine mid-term chemical engine is considered an intermediate step in the development of the far term fluorine/hydrazine engine so that if a decision was made to proceed directly to the development of the far term engine, $100M would be needed. Mid-term and far term sail states are also coupled.

Table 1: Propulsion System Costs in FY97 $M

	Incremental Technology Development	Flight System First Unit	Flight System Recurring	Operations Increase
Chemical				0
Current Technology	N/A	N/A	10 - 15	
MSR '05 Ascent Systems	29	20	15	
LOX/Hydrazine	60	25	20	
Flourine/Hydrazine	40	30	25	
Solar Electric				0 - 10
NSTAR	N/A	25 - 35	15 - 25	
NSTAR2	8	25 - 35	15 - 25	
NSTAR3	24	25 - 35	15 - 25	
Direct Drive/TAL	26	25 - 35	15 - 25	
Solar Sail				0 - 10
10 g/m2	11	9	7	
5 g/m2	9	12	10	

4. Missions

The mission information given in the summaries below was primarily obtained from the roadmaps for the four NASA Space Science themes (Ref. 2-5). The figures referenced in the text are located at the end of the paper.

4.1 Comet Nucleus Sample Return

A Comet Nucleus Sample Return mission would obtain an approximately 0.5 kg sample - taken from one or more sampling sites - using a sub-surface sampling apparatus, such as a surface drill (Champollion-type lander) or a penetrator (ejected sample). A mother ship would return the sample to Earth. SEP or sail advances are enabling for all comets of interest to the scientific community, and NSTAR2 is currently being baselined for Champollion. An example mission to Comet Tempel 2 was used to illustrate the technology potentials for delivering a spacecraft to a comet in Figure 2. In the far term, a solar sail would offer the capability of accomplishing the mission on a smaller launch vehicle (Taurus/Star 37) and a potentially shorter flight time (< 7 yrs at a_c =

1 mm/s^2) but with the penalty that the mother ship could not be active during the rendezvous, eliminating some sampling schemes.

4.2 Europa Lander

A Europa Lander would study seismic vibrations, conduct chemical analyses of the surface ice and organics, and determine the interior structure of the moon. The trajectory being considered would require a Jupiter Orbit Insertion (JOI) and a Jovian satellite tour lasting approximately one year, followed by a descent to the surface. Regardless of the main propulsion system used to reach Jupiter, a significant portion of the delivered mass would be needed to transport a chemical propulsion system to Jupiter to complete the tour and arrive at the target. As shown in Figure 3, a current chemical design (Isp = 317 s) has a net delivered mass to Europa of about 120 kg using an Atlas launch vehicle (Ref. 6), while far term SEP or sail would each provide approximately the same delivered mass on a Delta 2 7925. For the low-thrust trajectories used in this study, the flight times for the advanced far term systems range from about 18 to 48 months greater than the current study. However, for a more detailed analysis, a greater effort would be made to optimize the trajectory for the chosen system, potentially leading to shorter flight times.

4.3 Europa Orbiter

The Europa Orbiter's primary objectives would be to measure the thickness of the surface ice layer and determine the existence of a subsurface ocean. Although a Europa Orbit Insertion (EOI) maneuver would be necessary, the trajectory profile is similar to that for the Europa Lander, with the same need for a chemical system at Jupiter. With current technology, there is a trade off between launching on an Atlas with chemical propulsion or on a Delta using NSTAR. Small payload benefits are achieved for both the mid-term and far term chemical and SEP systems.

4.4 Interstellar Probe

The objective of the Interstellar Probe mission would be to cross the solar wind termination shock and heliopause, making significant penetration into interstellar space. The termination shock location is estimated to be located at 80 - 90 AU, with the heliopause further out. Far term technology enables this mission, with an ultra-far term (< 5 g/m^2 loading) solar sail allowing the use of a Delta 2 7925 launch vehicle.

4.5 Io Volcanic Observer

The Io Volcanic Observer would use visible and thermal imaging, high resolution ultraviolet spectroscopy, and radio tracking to study Io's volcanoes, atmosphere, and gravity fields and their interactions. Although this mission was not studied in detail, the profile would be similar to that for the Europa Orbiter, so the benefits are assumed to be the same.

4.6 Jupiter Deep Multi-Probes

The Jupiter Deep Multi-Probes would send two or three probes to 20 - 100 bar depths at different latitudes, expanding upon the Galileo probe science. Data relay would be through the carrier spacecraft. In current technology, NSTAR provides the best performance of delivering a spacecraft to Jupiter (Fig. 4), with both NSTAR2 and NSTAR3 giving a 20% performance improvement. A far term sail has a similar performance, but the sail itself would need to be large (about 220 m on a side) which raises questions about the practicality of using the system.

4.7 Mars Sample Return

The first Mars Sample Return mission is scheduled for launch in 2005, with follow ons tentatively planned for 2009 and 2013. The '05 baseline is a Delta 3 launch vehicle to carry a 600 kg orbiter and a 1400 kg lander (which includes a 700 kg ascent vehicle) (Ref. 7). Advances in chemical ascent propulsion systems - incorporating a high thrust engine, lightweight components, and low temperature propellants - are enabling for this mission. SEP and far term solar sail capability would give substantial performance benefits to Mars in delivering net spacecraft mass to Mars, at the expense of flight time (Fig. 5). However, the current plan is to reuse the '05 hardware in '09 to reduce cost. *In situ* propellant production is another expected technological advancement that should be considered in planning this program.

4.8 Mercury Orbiter

A Mercury Orbiter would be a polar-orbiting spacecraft with a full suite of remote sensing instruments to generate a detailed global characterization of the planet, as well as study solar phenomena. Both chemical and SEP systems could deliver approximately the same net mass to Mercury on a Delta 2 7925, with SEP producing significantly shorter flight times (Fig. 6). Far term sail indicates even greater performances increases and would allow insertion into a more desirable sun synchronous orbit.

4.9 Neptune Orbiter/Triton Exploration

A Neptune Orbiter mission would also include Triton flybys so that the full compliment of remote sensing instruments could characterize both the planet and its largest moon. If the far term spacecraft technology goal of a 50 kg net required delivered mass to Neptune is achieved, the mission could be done on a Delta 2 7925 using current propulsion technology. However, it would require at least an 11 year trip time (Fig. 7). A mid-term SEP system could cut nearly two years off the flight time using the same launch vehicle. Far term SEP would reduce the launch vehicle needed to a Delta 2 7326, while a 5 g/m^2 sail would further reduce it to a Taurus/Star 37 with a flight time as low as 8.5 years. For the Neptune Orbiter mission, aerocapture is assumed at the target. Accordingly, the net mass delivered for all systems has been reduced by 30% to account for a ballute.

4.10 Pluto/Kuiper Express

Pluto/Kuiper Express would be a flyby mission to provide the first proximity remote sensing of the Pluto/Charon system and a Kuiper object. The current baseline is a 2001 - 2004 launch on a Delta 2 7925 with a 10 - 12 year flight time using a Jupiter Gravity Assist (Ref. 8). NSTAR would provide a significant performance increase over the current chemical systems, allowing both a smaller launch vehicle and shorter flight time to Pluto (Fig. 8). Mid-term SEP systems would give up to a 20% performance improvement but with a significant increase in cost. Since a mid-term launch date is targeted, the far term possibilities are probably academic. However, the SEP system would give only a slight increase in capability from the mid-term.

4.11 Solar Polar Imager

A Solar Polar Imager would be placed in a 1 AU orbit at 90° inclination, with a 90° separation from Earth at each ecliptic crossing. This type of orbit will allow solar observation from a non-Earth vantage point so that three dimensional solar structures, such as the longitudinal extent and rotational curvature of coronal features, can be better studied. Far term solar sail technology enables this mission.

4.12 Solar Probe

The Solar Probe mission will be the first close flyby (4 solar radii) of a star. Currently, the chemical propulsion mission design delivers an approximately 140 kg net spacecraft mass to its solar encounter (Ref. 9). NSTAR3 would give a 70% payload increase. A far term sail could provide an even greater payload increase, a possible reduction in flight time, and potentially a better scientific trajectory, such as having the perihelion occur over a pole.

4.13 Titan Explorer

A Titan Explorer would primarily study the distribution and composition of organics on the Saturnian moon, as well as look at the dynamics of the global winds. Aerocapture at Titan, avoiding a Saturn Orbit Insertion (SOI) is currently the most attractive trajectory option. An NSTAR on a Delta 2 7326 would be able to deliver about 200 kg net spacecraft mass to the surface (Fig. 9). Mid-term SEP would only improve that by about 10%. However, a 10 g/m^2 sail could result in a smaller launch vehicle and possibly a reduced flight time as well. A far term sail would provide a substantial performance improvement.

4.14 Other Missions

4.14.1 Astronomy Missions in Deep Space Orbits. Missions that fall into this category include the Next Generation Space Telescope (NGST) (1 X 3 AU orbit), the Terrestrial Planet Finder (TPF) (5.2 X 6.2 AU orbit), the High Throughput X-Ray Spectrometer (HTXS) (L2 point), the Laser Int. Space Antenna (LISA) (1 AU, 20° lag), the Advanced Radio Interferometry between Space and Earth (ARISE) (22,000 - 77,000 km), and the Planetary Imager (5 AU circular). Of these, HTXS and ARISE could be accomplished efficiently with current chemical technology. NGST and TPF show significant performance (i.e. figure of merit) improvements using a SEP or sail system instead of a chemical one. The other missions were not studied in any detail.

4.14.2 Comet and Asteroid Rendezvous and Main Belt Asteroid Sample Return. A Large Asteroid Orbiter would provide a detailed global characterization of a main belt asteroid such as Ceres. Although the Comet Rendezvous and Main Belt Asteroid Sample Return missions were not explicitly mentioned in the Space Science Strategic Plan, they were part of the SSES input to that Plan and are candidates for future Discovery missions. All of these missions would benefit strongly from low thrust propulsion.

4.14.3 Non-Keplerian Orbits. Several missions, such as those requiring halo orbits or the Geostorm meteorology mission, which require a spacecraft to be placed in a non-Keplerian orbit are enabled by solar sail technology.

5. Conclusions

Although it was not possible to examine every potential mission in this study, a diverse spectrum of interplanetary targets, science objectives, and mission types are represented. A summary of the study results, by mission is given in Table 2.

Table 2: Trades Study Performance Summary

	BENEFIT FROM NEAR-TERM TECHNOLOGY RELATIVE TO BEST CURRENT TECHNOLOGY		ADDITIONAL BENEFIT FROM MID-TERM TECHNOLOGY RELATIVE TO BEST NEAR-TERM TECHNOLOGY			ADDITIONAL BENEFIT FROM FAR-TERM TECHNOLOGY RELATIVE TO BEST MID-TERM TECHNOLOGY		
	CHEMICAL ASCENT	SEP NSTAR2	CHEMICAL LOX	SEP NSTAR3	SAIL 10 G/SQM	CHEMICAL FLUORINE	SEP D/O,TAL	SAIL 5 G/SQM
CATEGORY 2								
MARS SURVEYOR								
ORBITERS								
LANDERS								
SAMPLE RETURN	[illegible]							[illegible]
EUROPA ORBITER			3a	3a		3b	3b	
PLUTO EXPRESS				3a				3a
SOLAR PROBE				2a				[illegible]
CNSR		[illegible]					3b	[illegible]
JUPITER MULTIPROBE		3a						
NGST				2c				3c
PLANET FINDER				2c	[illegible]			3c
CATEGORY 3								
HTXS				[illegible]				3c
CATEGORY 4								
LISA				3c				
PLANETARY IMAGER				3c				
EUROPA LANDER							[illegible]	[illegible]
IO VOLCANIC OBSERVER			3c	3c		3c		
NEPTUNE ORBITER				[illegible]			3b	[illegible]
TITAN EXPLORER					3c			[illegible]
VENUS LABORATORY								
INTERSTELLAR PROBE								[illegible]
SOLAR POLAR IMAGER					[illegible]			[illegible]
MERCURY ORBITER				[illegible]	[illegible]			[illegible]

BENEFITS:
1 = ENABLING FOR LAUNCH ON DELTA 7925 (ATLAS FOR NGST & PLANET FINDER)
2 = STRONGLY ENHANCING: +50% DELIVERED MASS AND/OR -2 YEARS FLIGHT TIME
3 = ENHANCING: +20% DELIVERED , -1 YEAR FLIGHT TIME, AND/OR SMALLER LAUNCH VEHICLE
a = FULLY DEFINED, b = WELL DEVELOPED CONCEPT, c = IMMATURE CONCEPT

As indicated previously, a greater emphasis was placed on Space Science Strategic Plan priority missions and, within that category, those missions which would most clearly benefit from advanced propulsion. Using these missions as benchmarks, the study found:

- Advanced chemical systems are enabling for Mars Sample Return and provide some performance enhancements for several other missions, but at a very high development cost.
- The near- and mid-term solar electric systems give substantial benefits for moderate costs, while the far term system yields moderate additional benefits for only a small number of missions.
- The far term solar sail capability enables or significantly enhances several missions at a low development cost. Mid-term sail capability enables a couple of missions and serves as a stepping stone for the far term capability.

6. Recommended Investment Strategy and Sample Scenarios

Based on these findings, the recommended investment strategy gives priority to mid-term solar electric propulsion systems, ascent propulsion systems for a Mars sample return mission, and the first steps toward solar sail capability. Figure 10 shows one scenario for implementing the investment strategy.

7. Acknowledgments

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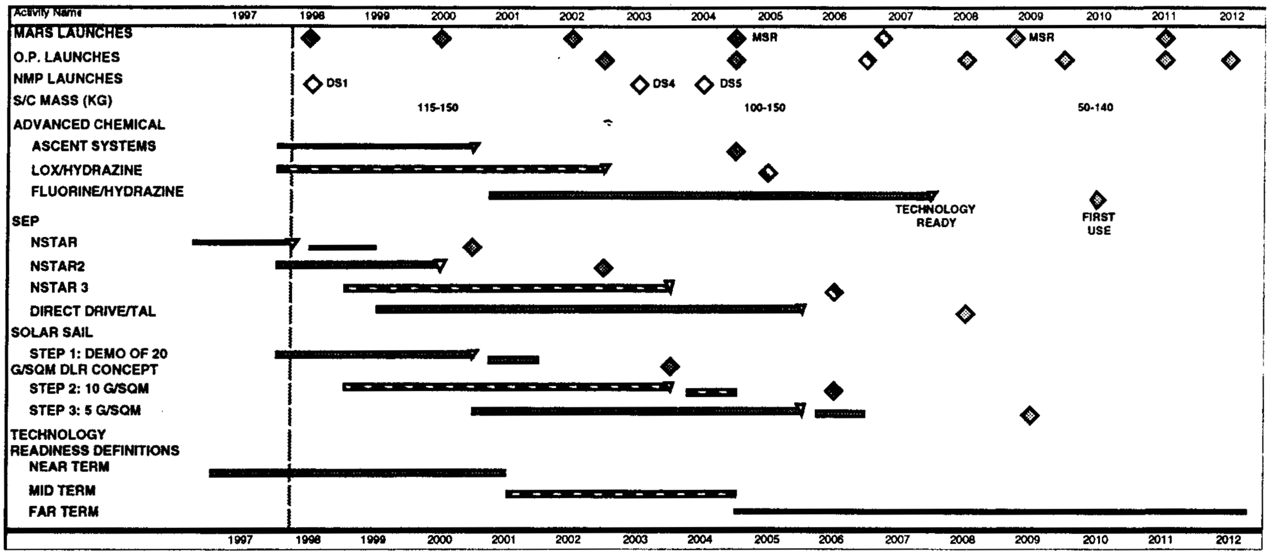

Figure 1: Schedule Elements Illustrating Aggressive Development in All Areas

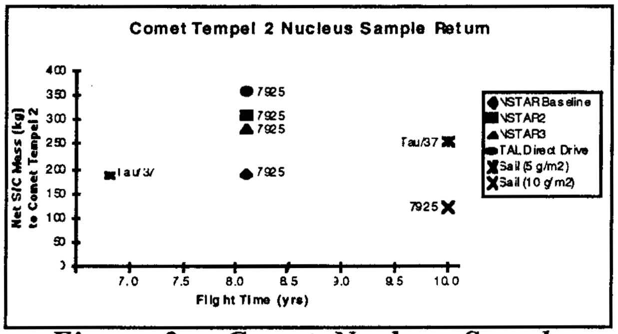

Figure 2: Comet Nucleus Sample Return

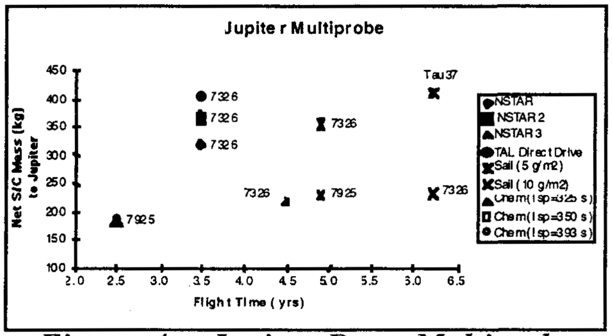

Figure 4: Jupiter Deep Multiprobe Mission

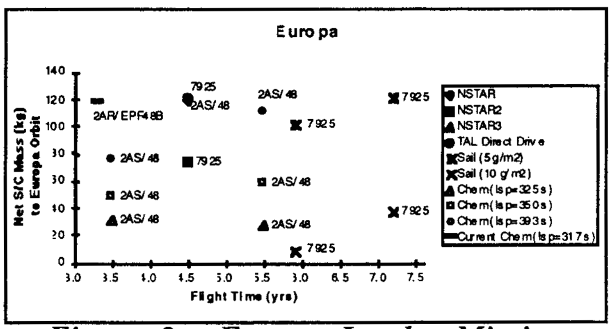

Figure 3: Europa Lander Mission

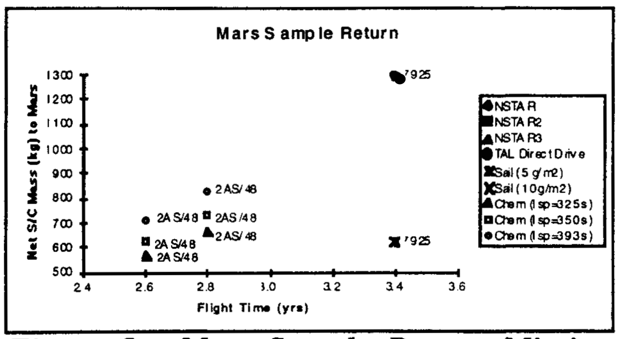

Figure 5: Mars Sample Return Mission

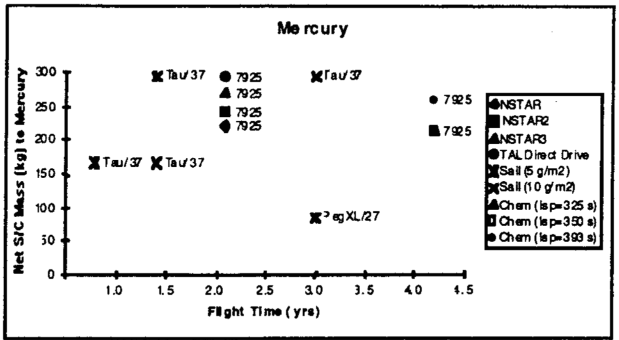

Figure 6: Mercury Orbiter Mission

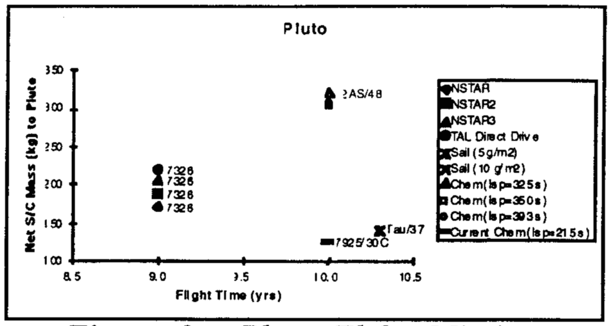

Figure 8: Pluto Flyby Mission

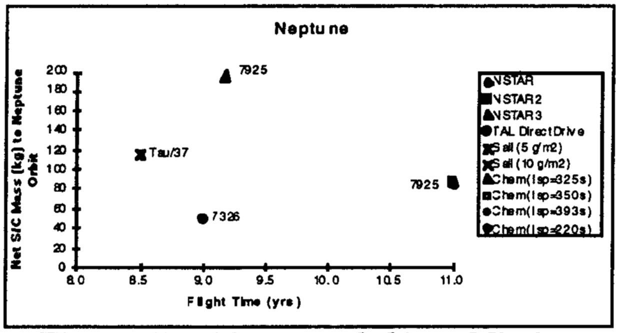

Figure 7: Neptune Orbiter Mission

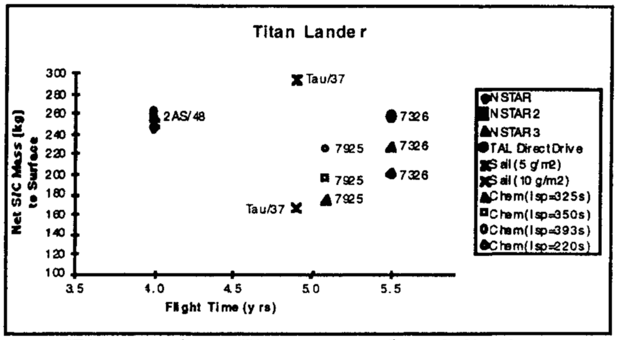

Figure 9: Titan Lander Mission

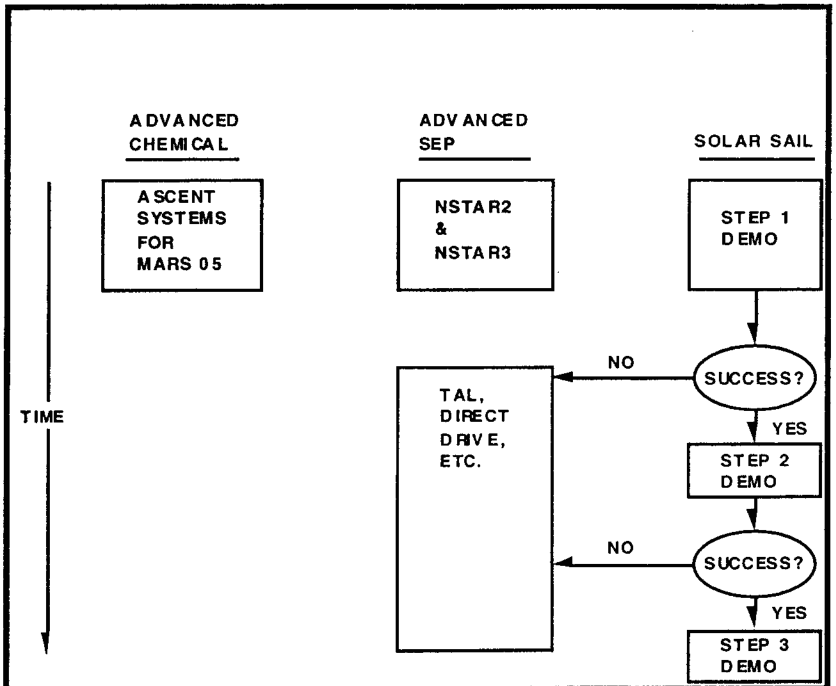

Figure 10: Recommended Investment Strategy